



**Upcoming ESTCP Demonstration of
Underwater UXO Detection and Classification
using AUV-Based Structural Acoustic Sonars**
Work Supported by SERDP & ESTCP

Presented by
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Objective



- Present overview of Structural Acoustic Sonar
 - Acoustic color and feature classification
 - BOSS AUV
- Present ESTCP Demonstration Plan Details
 - Improvements to BOSS sonar
 - Measurement details
 - Goals

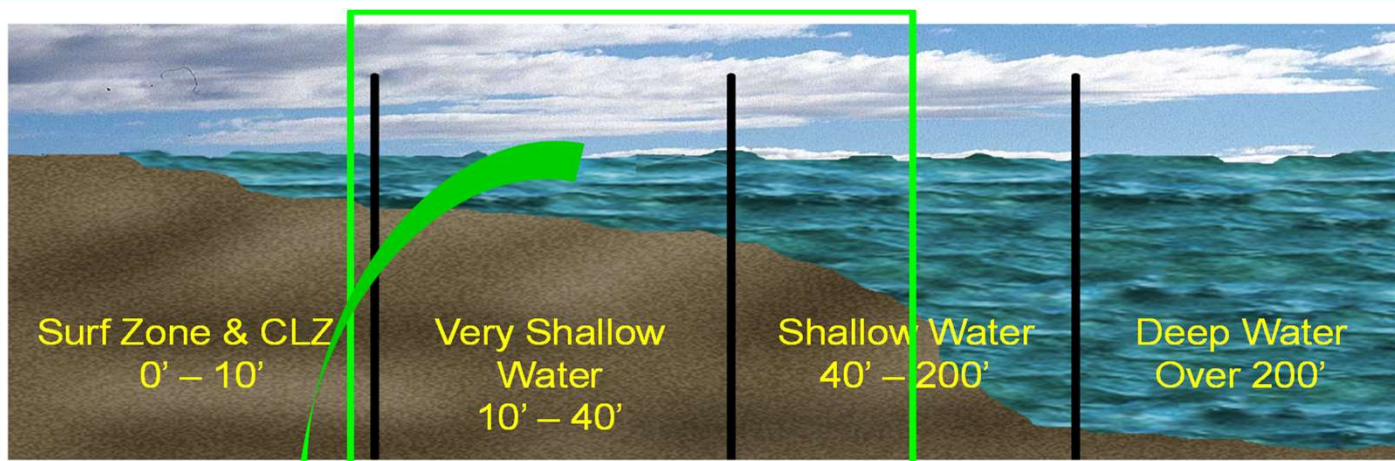
Background



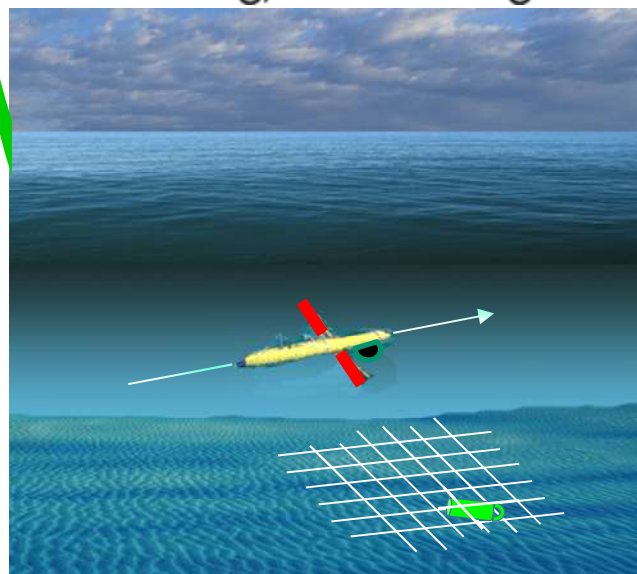
- ❑ **SERDP Projects MM-1513, MR-2103, and MR-2205:** Exploration of a SA-based sonar technology for detection and classification of underwater buried (and proud) UXO.
- ❑ **Acoustic Color:** An early innovation to support RVM feature-based target classification.
- ❑ **BOSS AUV sonar in the Gulf:** Demonstrated efficacy of SA/acoustic color approach.
- ❑ **Synthetic plus real apertures of the winged AUV:** Allowed formation of acoustic images with sufficient resolution to garner rough target shape, size, and burial angle.
- ❑ **ESTCP Demonstration Program:** Now underway using an improved “down-look” winged BOSS sonar together with one that is “side-looking”, each AUV-based.

Targeted Environment

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Down-Looking, Short Range Sonars

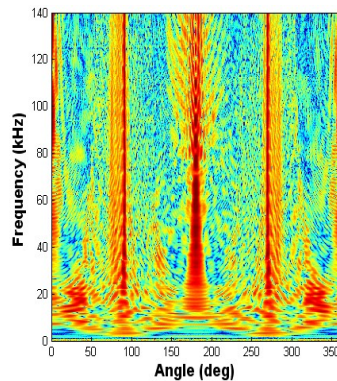
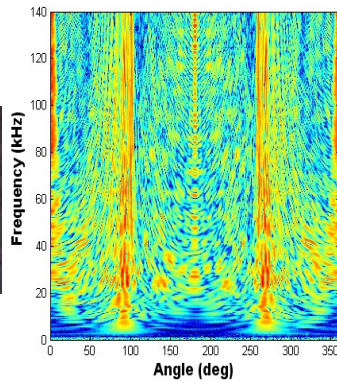


Target
Receiver
Source

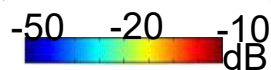
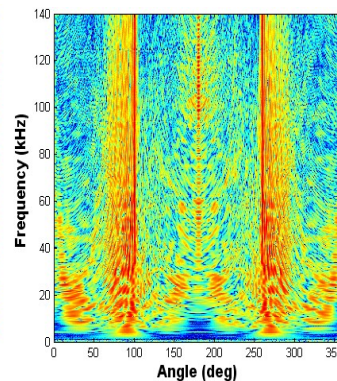
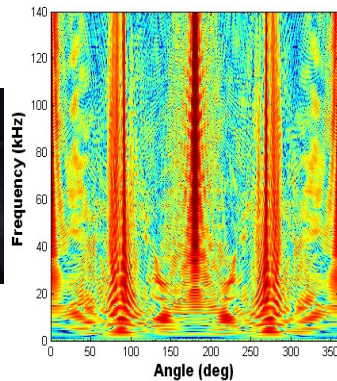
UXO Acoustic Signals

$$TS = 20 \log_{10} \left| \frac{P_{scat}(f, \theta)}{P_{inc}(f)} \frac{r_{scat}}{e^{ikr_{scat}}} \right| = 20 \log_{10} | \text{Acoustic Color} |$$

80 mm
Mortar



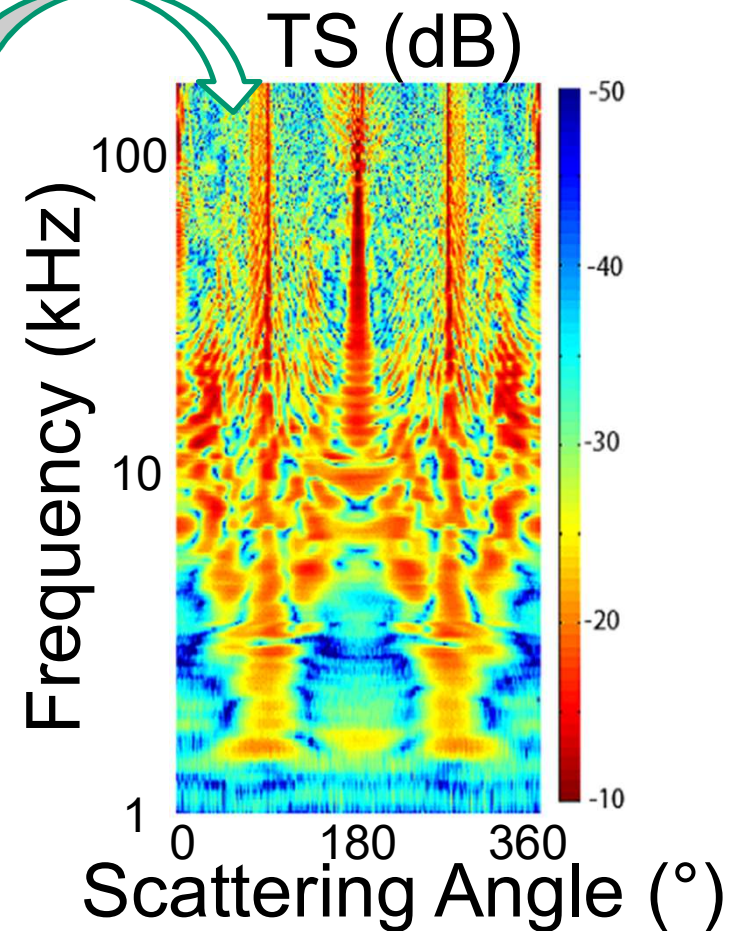
155 mm
Shell



5 inch
Rocket



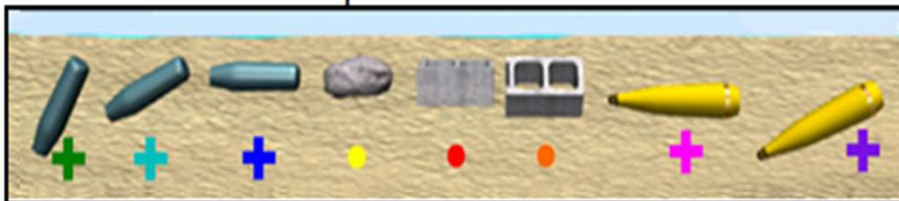
120 mm
Mortar



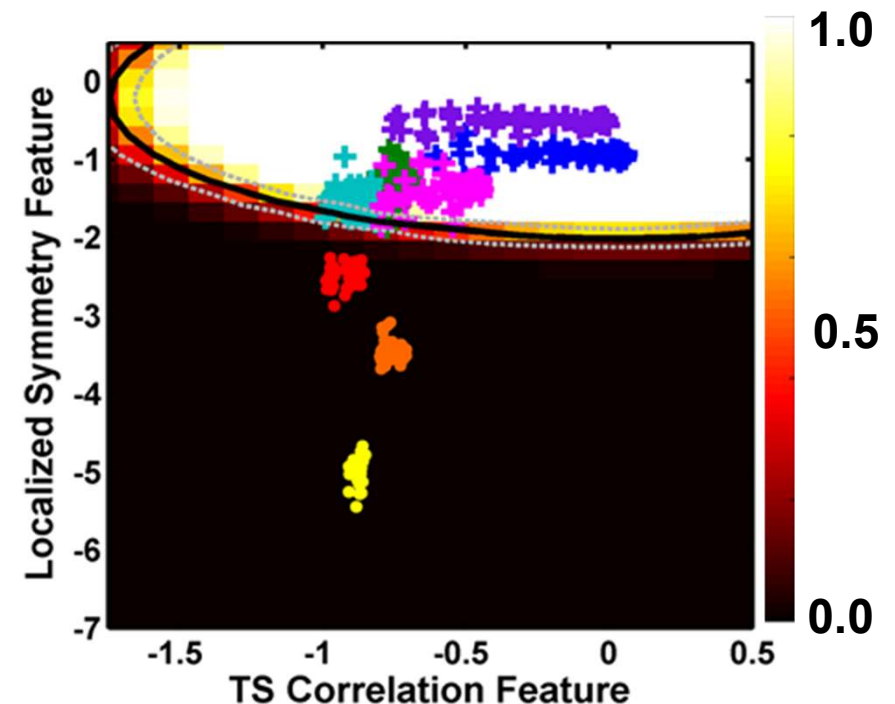
Early Success: Numerically Trained Classifier

A *numerically* trained RVM classifier applied to acoustic color synthetic array measurements made on eight targets buried in the NRL sediment pool was able to separate UXO from clutter targets with $P_C > 0.98$ and $P_{FA} = 0$.

Targets Buried in Sediment Pool



Probability that Target is UXO

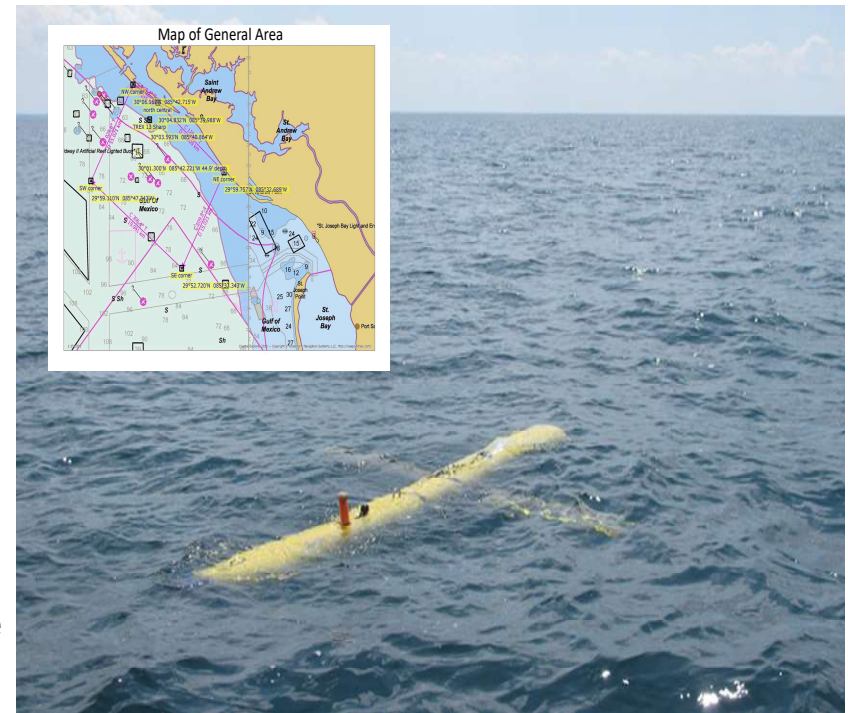
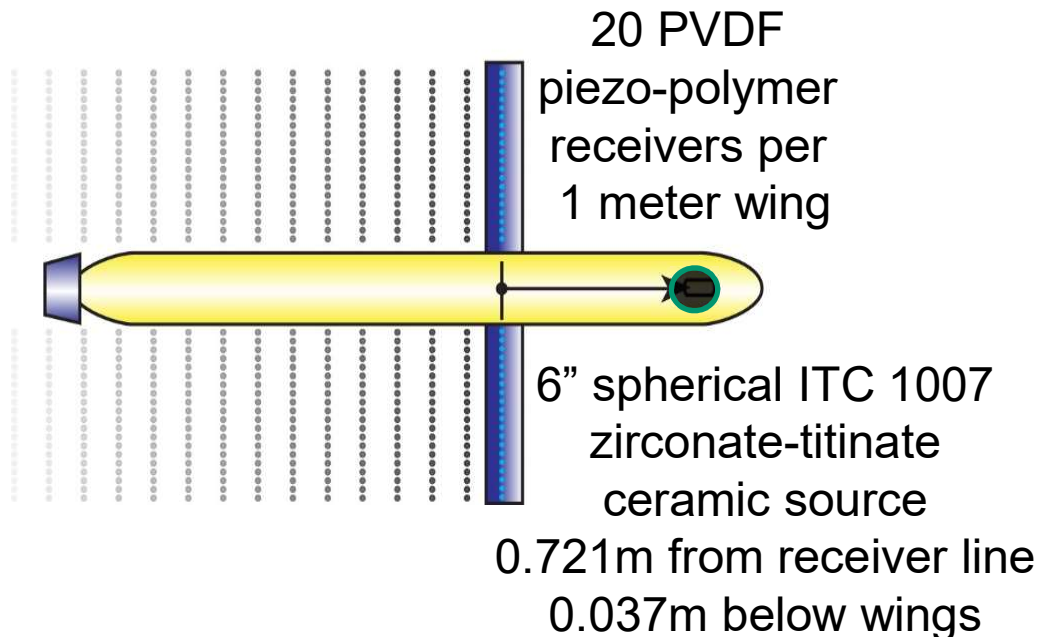


Later Success: BOSS in the Gulf of Mexico

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BOSS measurement exercises carried out June 23 and 24, 2013 off the Panama City, FL coast

Stephen Schock's BOSS

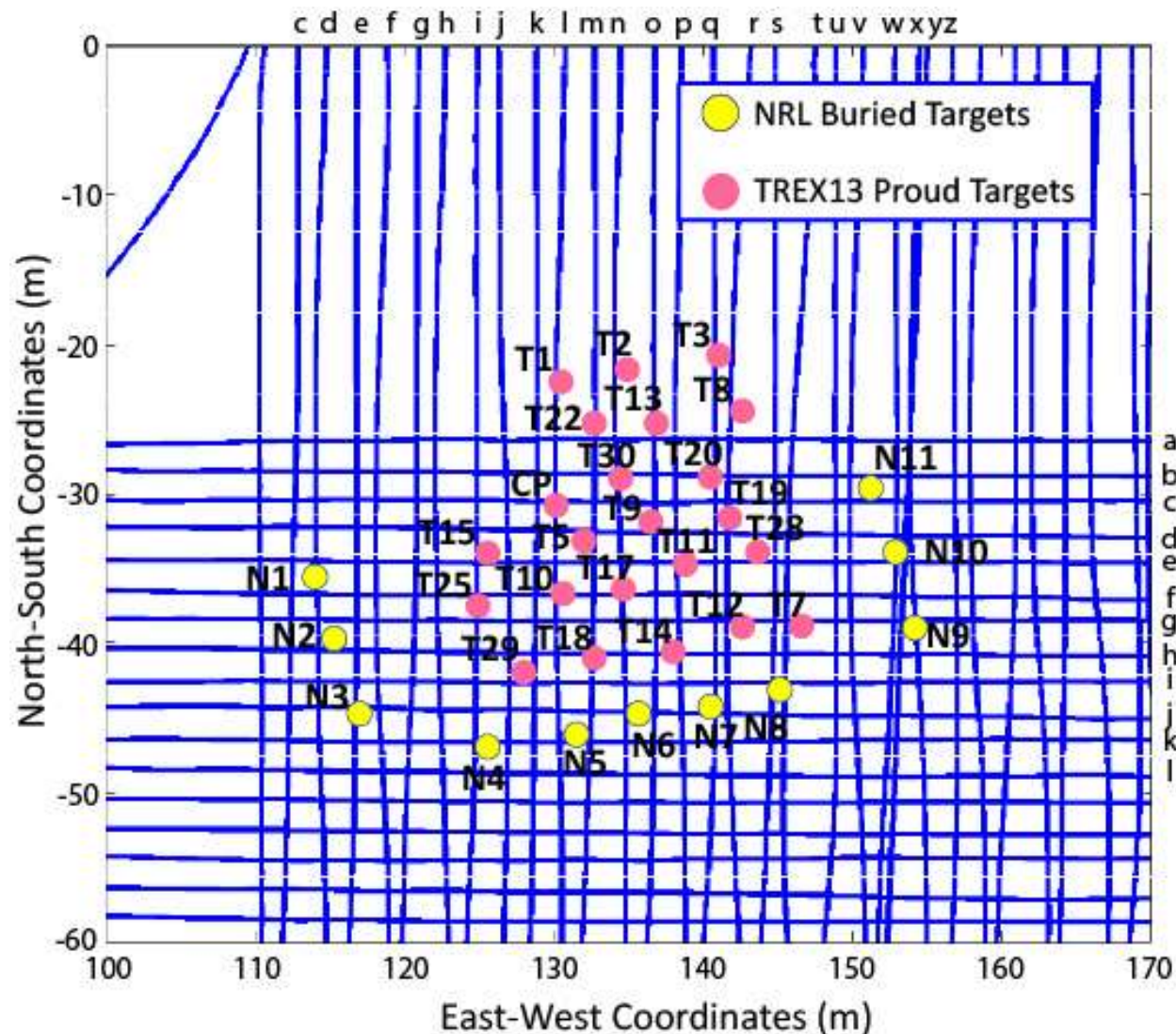


BOSS Flights: R. Holtzapple & J. Lopes, NSWC; H. Duplantis, Bluefin Robotics; D. Amon & H. Simpson NRL

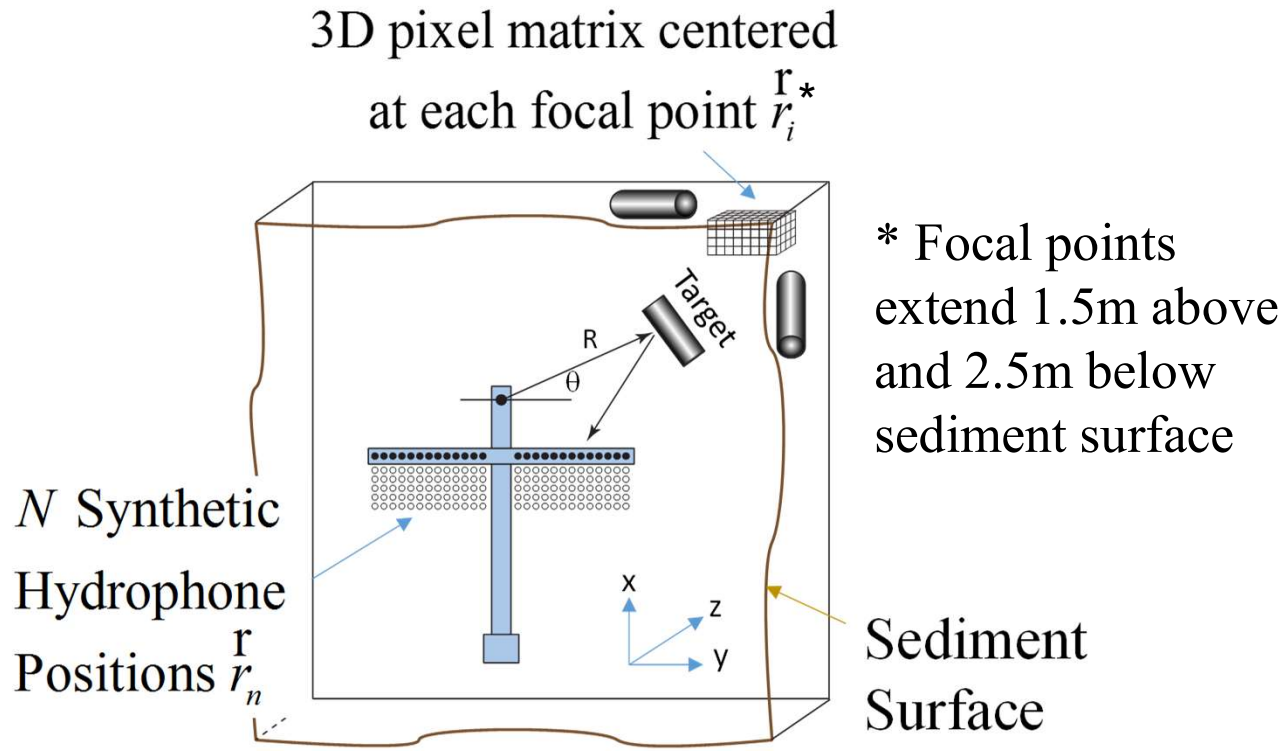
Proud (TREX 13) and Buried (NRL) Targets

PROUD TARGETS				NRL EPOXY-FILLED BURIED TARGETS	
T1	DEU Trainer	T14	Scuba Tank w/water w stem	N1	5 inch Rocket nose-up 60°
T2	Rock	T15	2:1 Aspect Phone Pole Section	N2	5inch Rocket nose-up 30°
T3	55 Gallon Filled Drum	T17	2ft Aluminum Cylinder	N3	5inch Rocket horizontal
T5	5:1 Aspect Phone Pole Section	T18	Cement Block	N4	155mm Projectile horizontal
T7	3ft Aluminum Cylinder	T19	Tire	N5	155mm Projectile horizontal 90°
T8	155mm Projectile w/o collar	T20	Aluminum UXO Replica	N6	155mm Projectile horizontal 20cm
T9	155mm Projectile w/ collar	T22	Original Material UXO	N7	155mm Projectile nose-up 30°
T10	Panel Target	T25	Bullet #1	N8	155mm Projectile nose-up 60°
T11	152mm TP-T	T28	155mm Projectile w/collar	N9	120mm Mortar
T12	81m Mortar	T29	Bullet #2	N10	Large Rock (no filler)
T13	Scuba Tank w/water w/o stem	T30	Finned Shell #1	N11	Cinder Block (no filler)
CP	Aluminum Panel (D. Cook)				

Buried and Proud Target Field & North/South & East/West Flight Paths



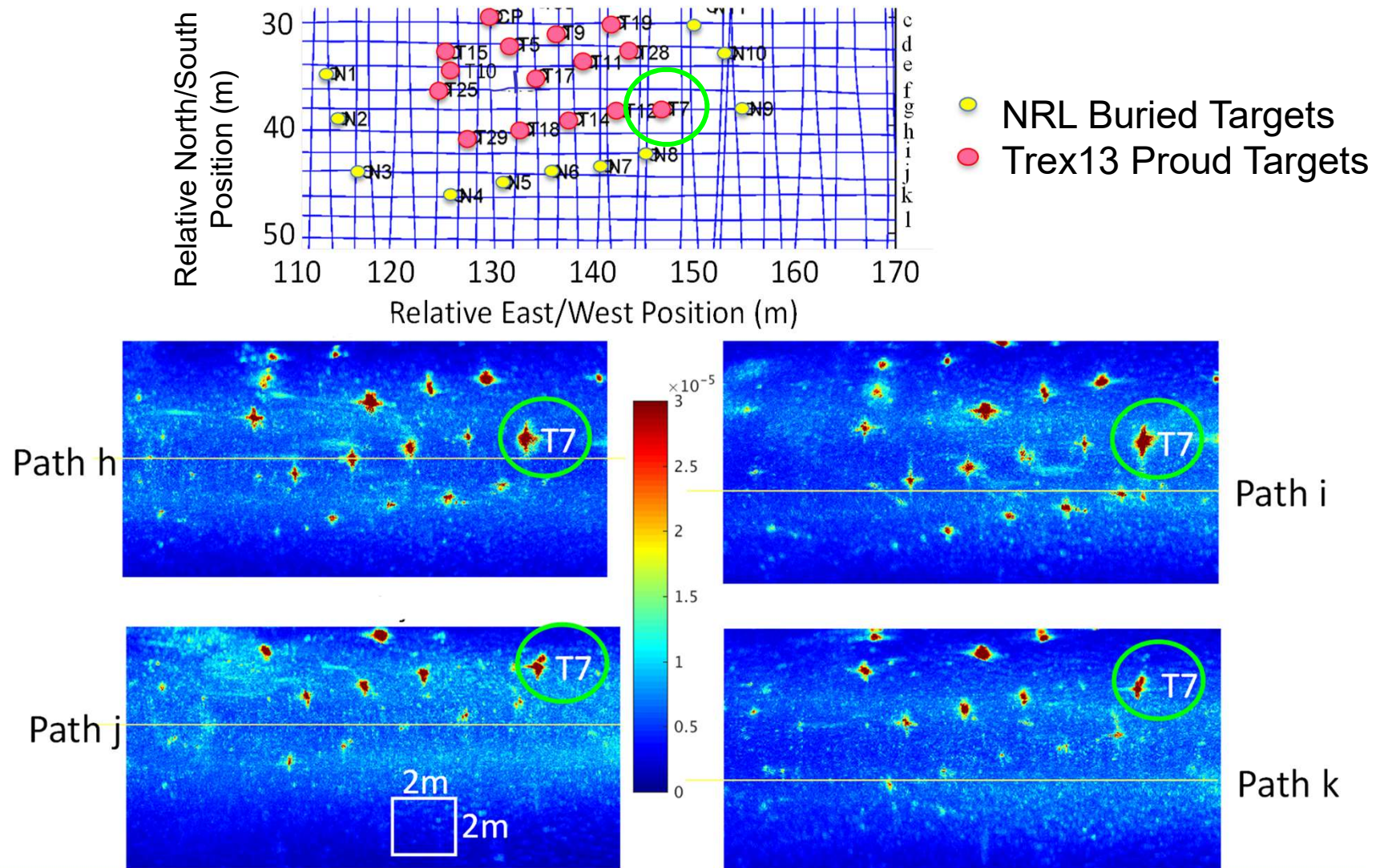
Images Generated using Time-Delay Beamforming



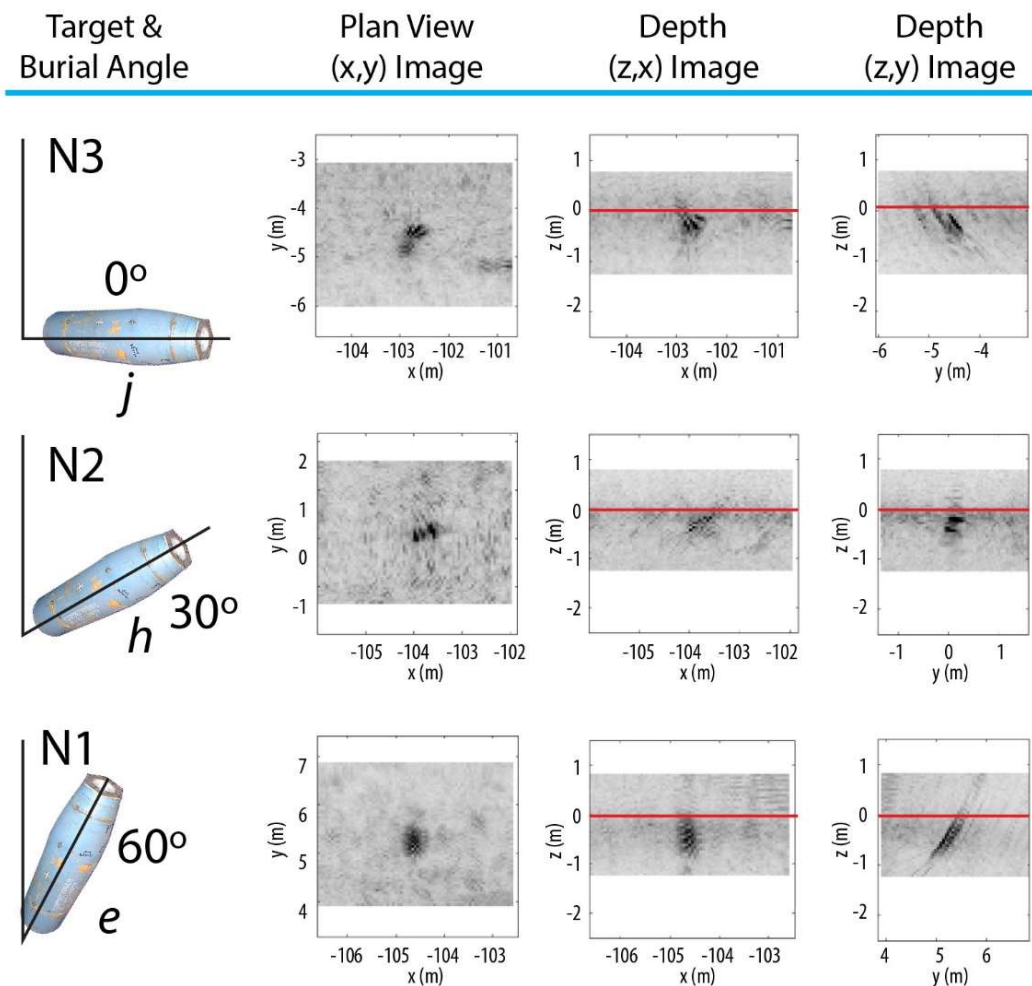
$$\text{Image Strength at } \mathbf{r}_i \equiv \sigma(\mathbf{r}_i) = \frac{1}{N} \sum_{n=1}^N 4\pi |\mathbf{r}_n - \mathbf{r}_i| d_n \left(\frac{\mathbf{r}_n}{|\mathbf{r}_n|} \cdot \frac{\mathbf{r}_n - \mathbf{r}_i}{|\mathbf{r}_n - \mathbf{r}_i|}, \frac{|\mathbf{r}_n - \mathbf{r}_i|}{c} \right).$$

$$\text{where } d_n \text{ is the inverse Fourier transform of } D_n \text{ and } D_n \left(\frac{\mathbf{r}_n}{|\mathbf{r}_n|} \cdot \frac{\mathbf{r}_n - \mathbf{r}_i}{|\mathbf{r}_n - \mathbf{r}_i|}, \omega \right) = \sigma_i(\bar{\mathbf{r}}, \omega) \frac{e^{ik|\mathbf{r}_n - \mathbf{r}_i|}}{4\pi |\mathbf{r}_n - \mathbf{r}_i|}$$

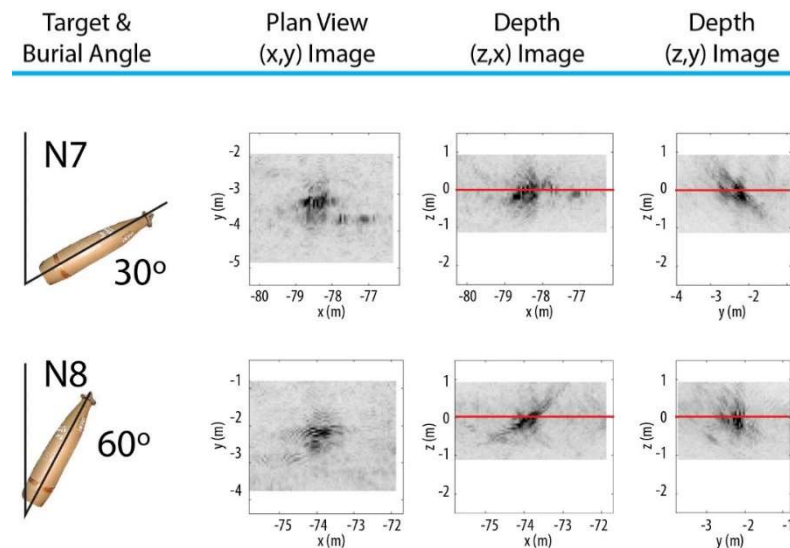
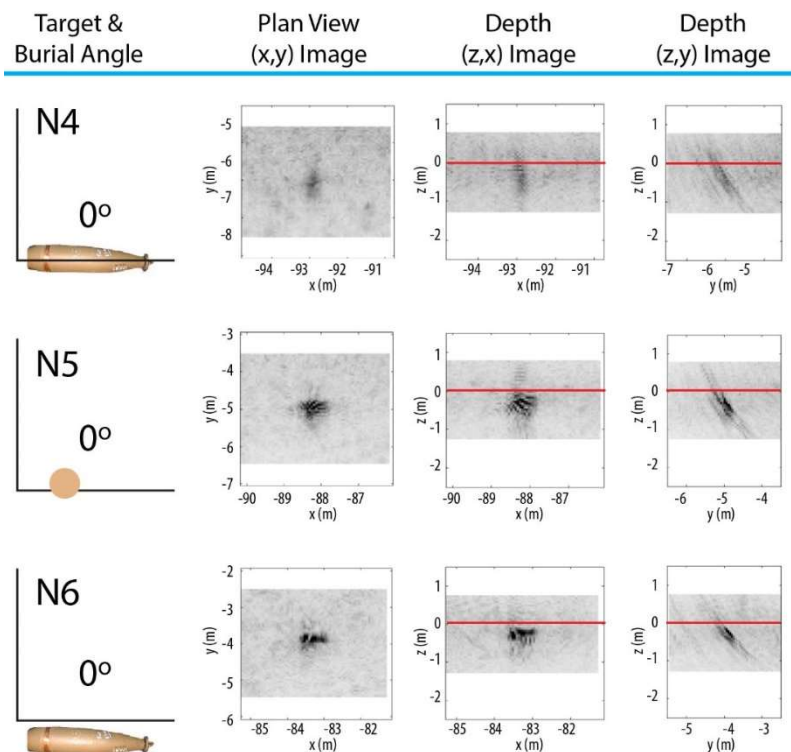
Volumetric Images: Used for Buried Target Detection



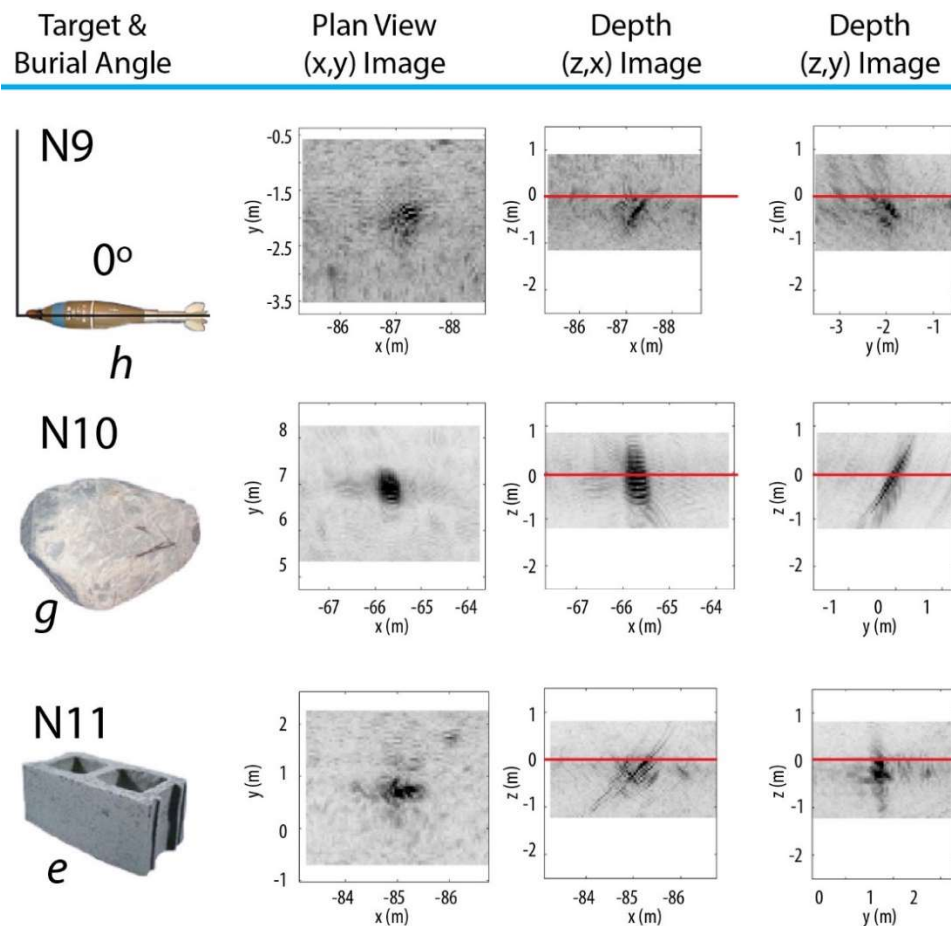
2-D Buried Target Images Projected onto the Three Orthogonal Planes



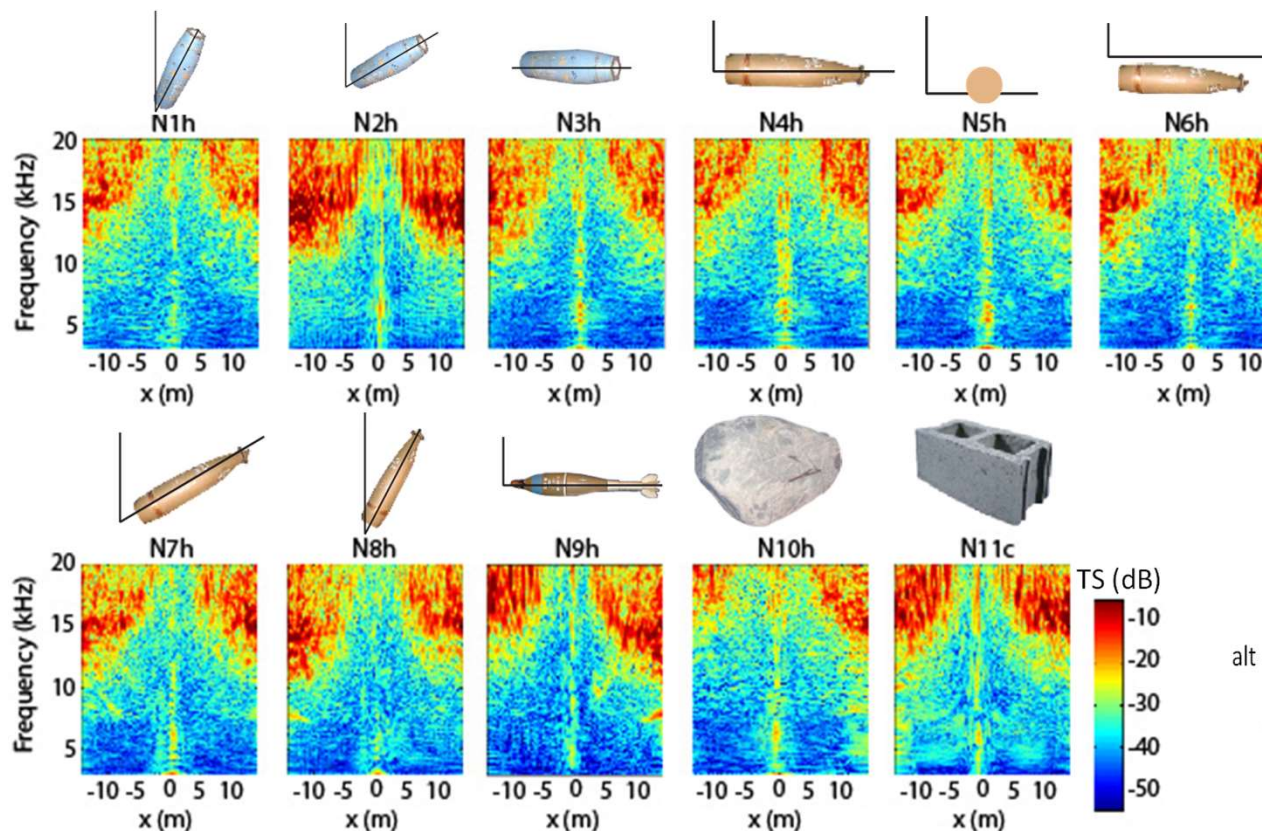
2-D Buried Target Images Projected onto the Three Orthogonal Planes



2-D Buried Target Images Projected onto the Three Orthogonal Planes



Buried Target Acoustic Color as Measured by BOSS

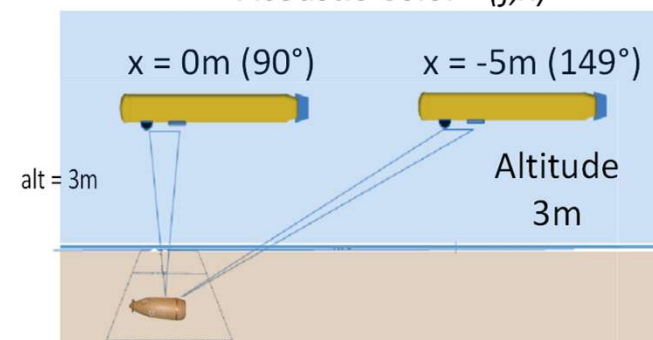


Sanity Check: Beam highlight peak TS for horizontal targets

Lab (ground truth) BOSS in Gulf

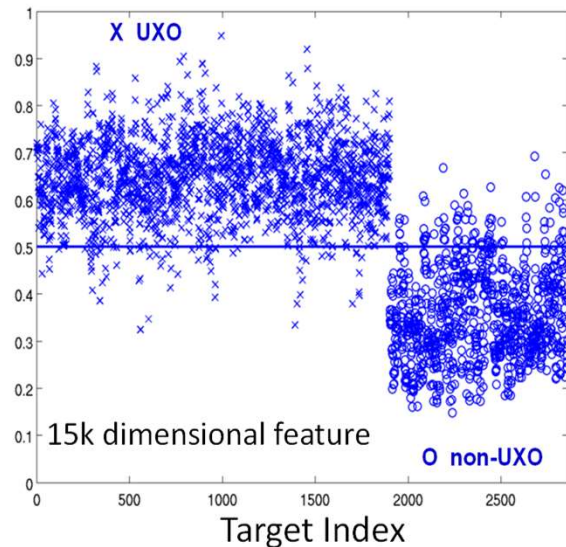
N3	-15dB	-15dB
N4	-13dB	-14dB
N6	-13dB	-18dB
N9	-16dB	-16dB

Acoustic Color' (f, x)

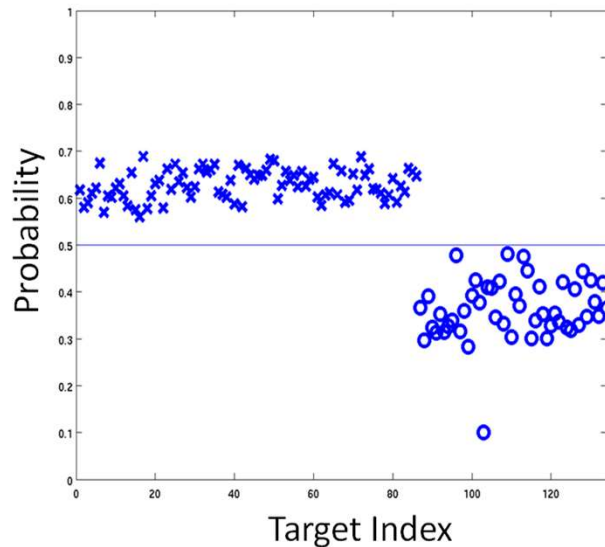


First Test: In principle can acoustic color separate these targets?

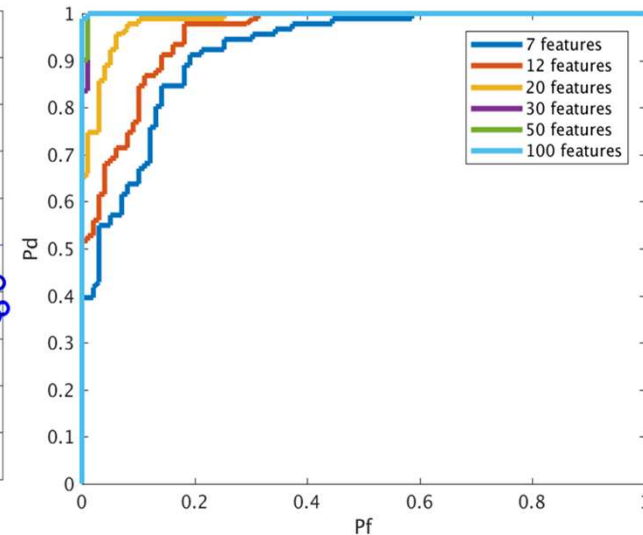
Probability (1-0) that a target detected on a particular receiver is a UXO



Probability that a target is a UXO using the product of the probabilities



ROC curves for various feature dimensionalities



More Definitive Classification Test: Train and Test on Different Targets

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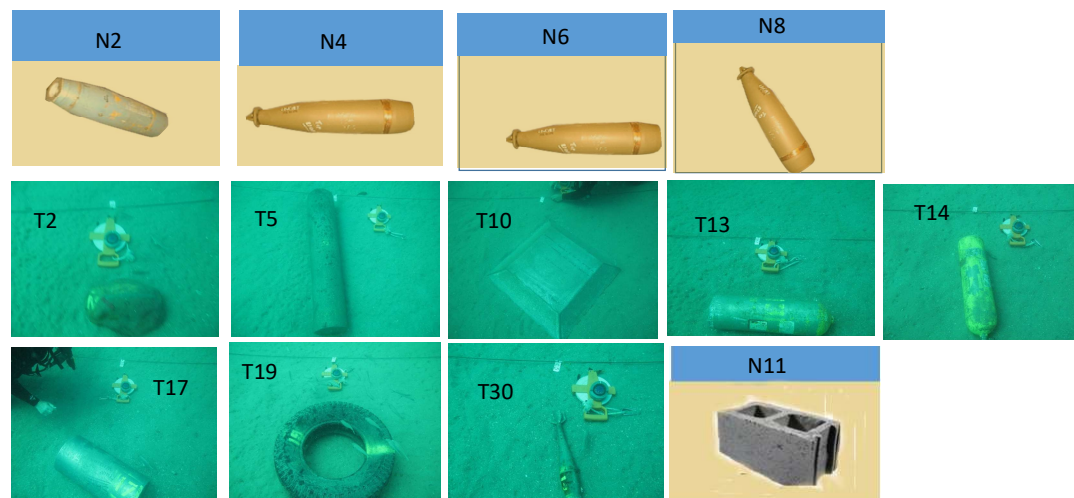
Train RVM on:

Buried Targets

UXO N2,N4,N6,N8
and clutter N11

Proud Targets

T2,T5,T10,T13,T14,T17,T19,T30



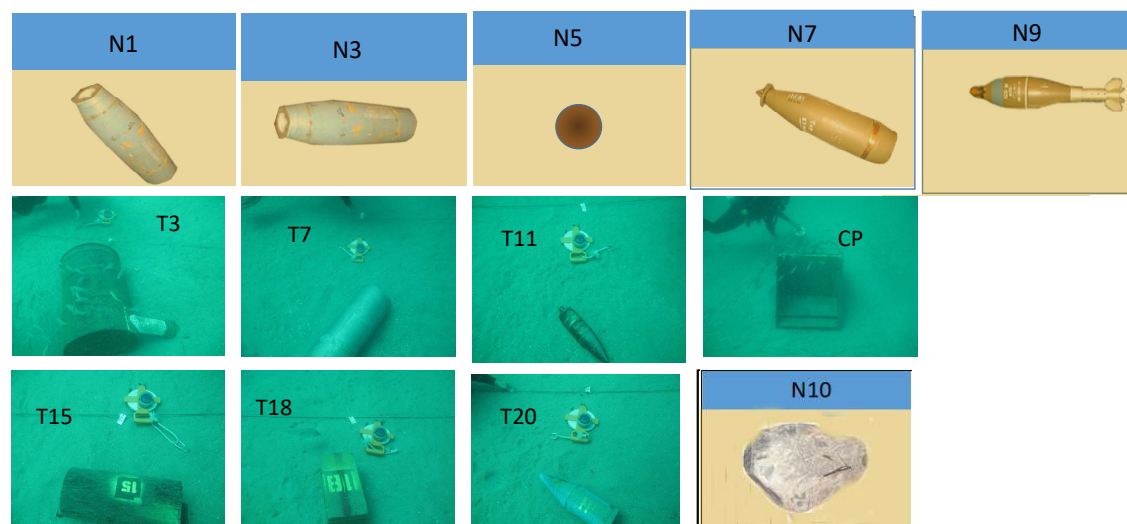
Test on:

Buried Targets

UXO N1, N3, N5, N7, N9
and clutter N10

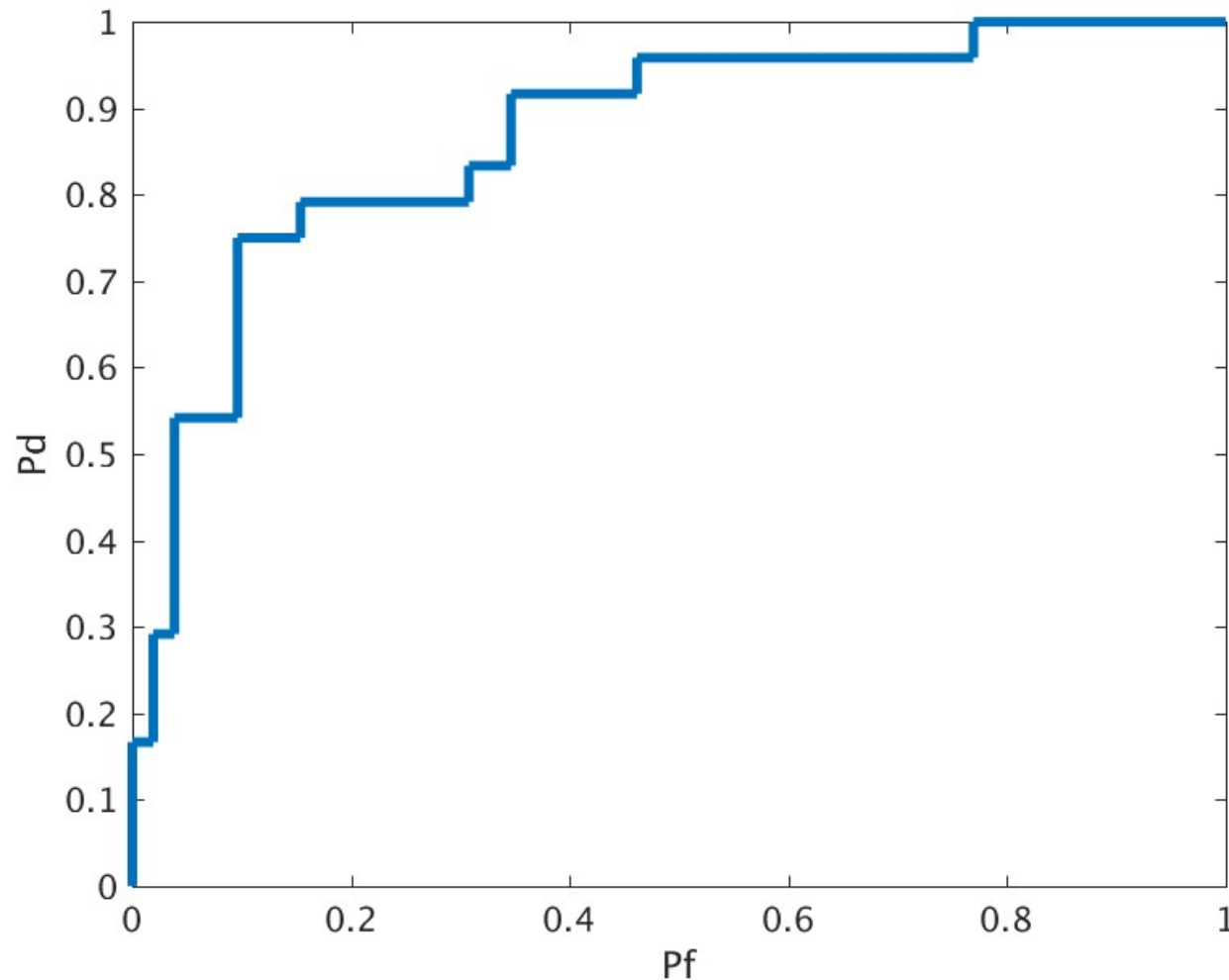
Proud Targets

T3, T7, T11, CP, T15, T18, T20



No use of proud UXO
(not epoxy-filled)

ROC Curve Summarizing RVM Classification Calls



Summary Performance

ROC curve performance is good given the overall limitations of the data (described later)

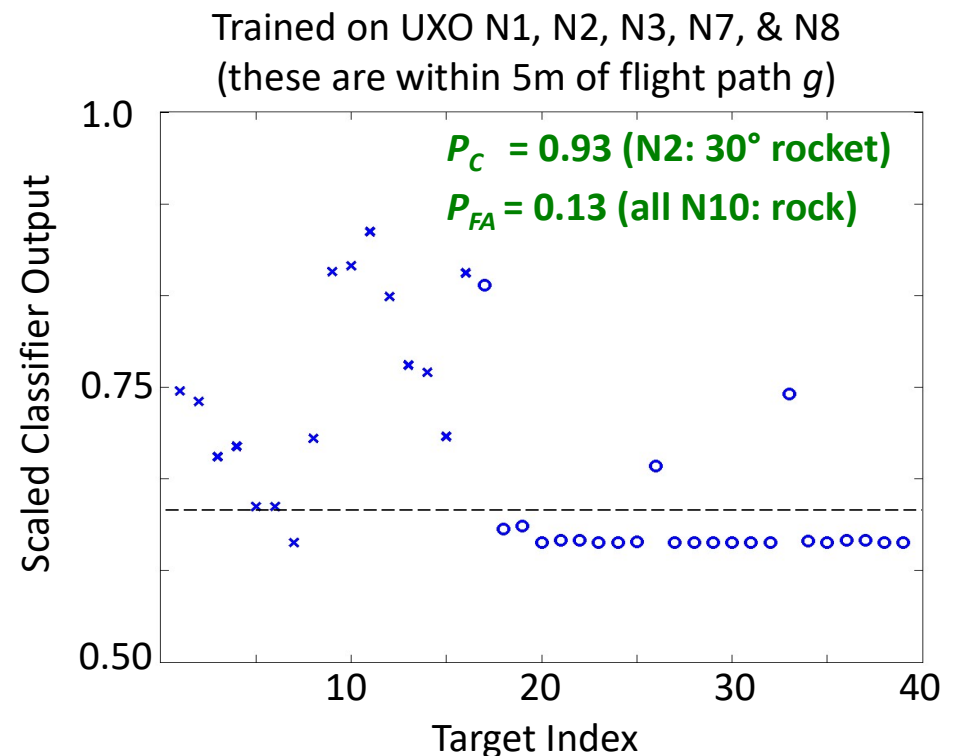
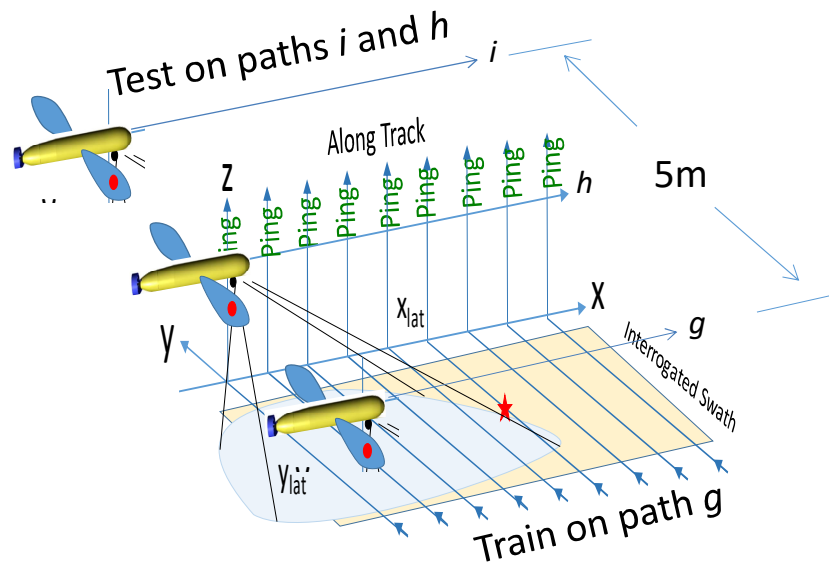
$P_C = 0.75$ & $P_{FA} = 0.12$ (0.50 threshold *mid-range*)
 $P_C = 0.92$ & $P_{FA} = 0.42$ (0.36 threshold)
 $P_{FA} = 0$ for all non-UXO except rock (0.71) and solid aluminum replica (0.25)

Given different shape (*flat panel*), material (*wooden pole sections*), and shape and material (*2:1 aspect wooden pole section*), that the RVM correctly calls these non-UXO is not surprising.

Given their metal materials and cylindrical shapes (*solid metal cylinders*), that they are nonetheless correctly called non-UXO is encouraging.

“Leave-one-out” Study Demonstrating Field Training Approach

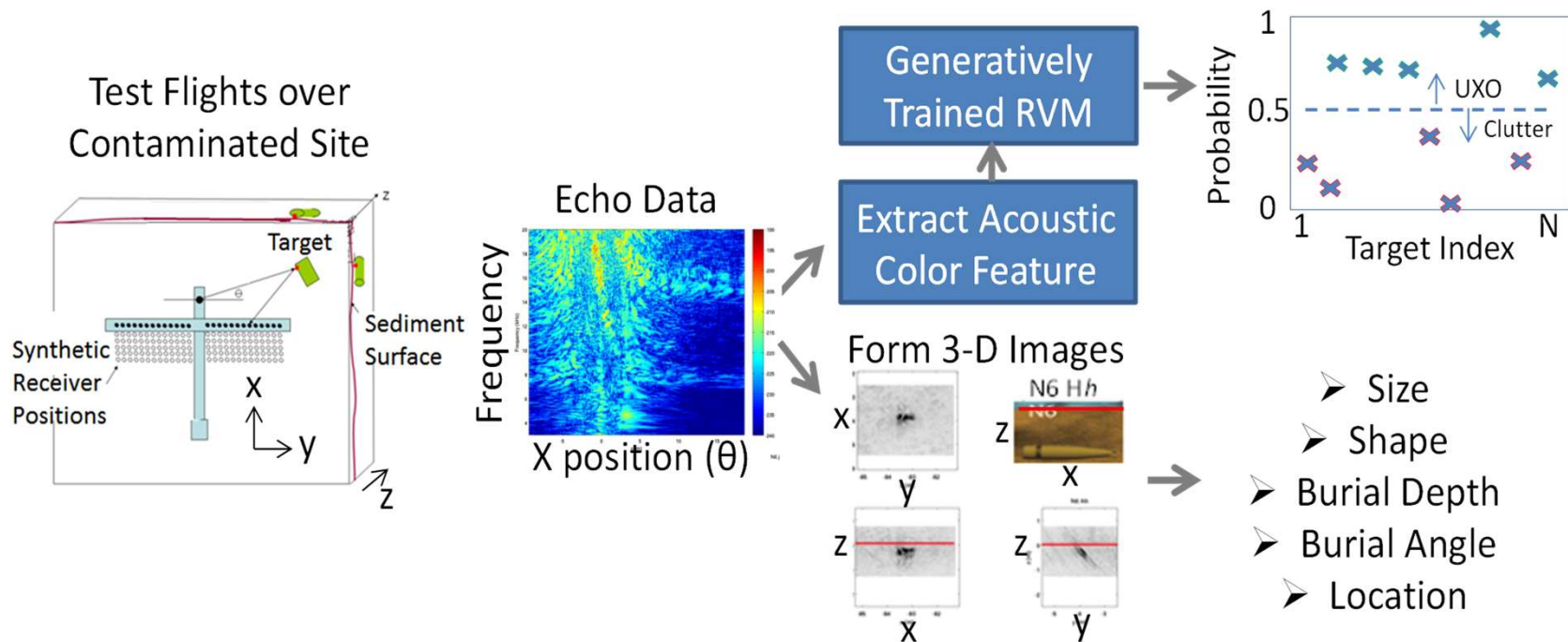
RVM acoustic color classifier trained generatively on only UXO targets detected with good S/N over one flight path and then tested on all targets as encountered on two other flight paths and non-UXO on training path.



Technology/Methodology Description Summary

Overall schematic of our methodology

- AUV sonar flies over target field and collects echo data from bottom
- Detected targets *localized & identified* with RVM acoustic color feature-based classifier *and* 3-D images

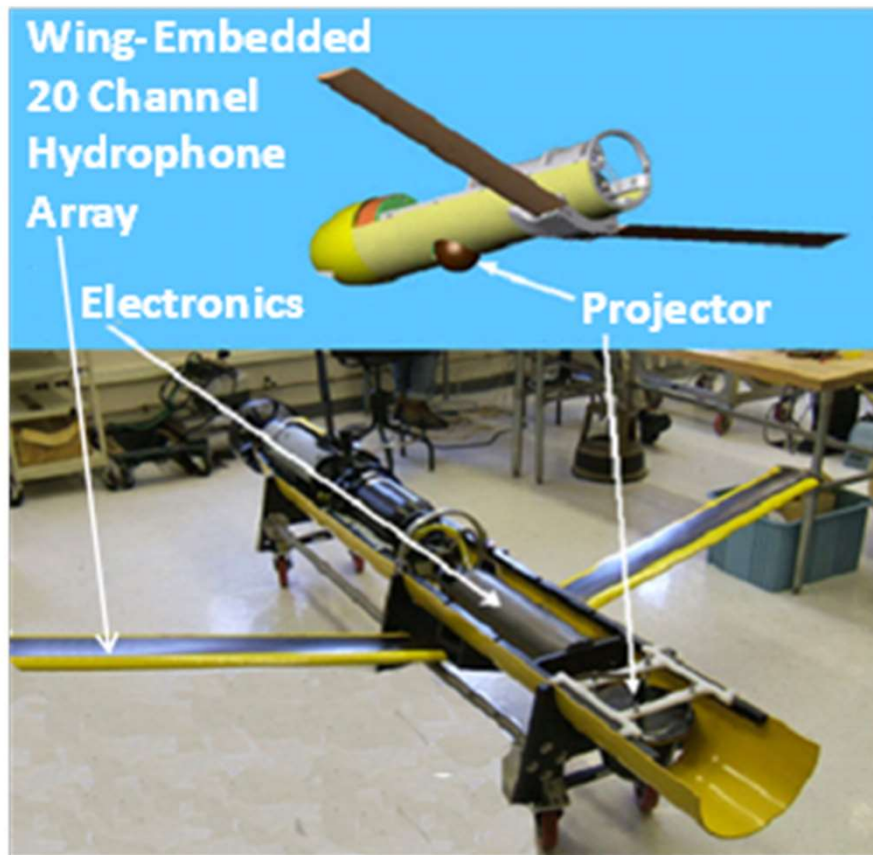


ESTCP DEMONSTRATION PROGRAM

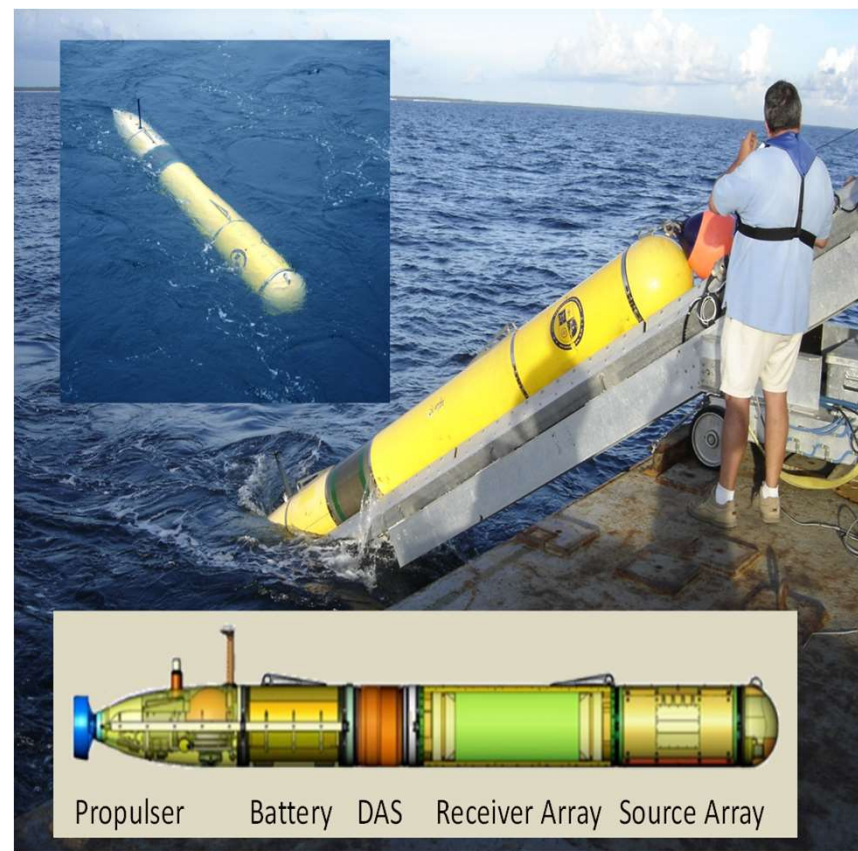
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Two AUV-Based Sonars Operating in the Approaches to Boston Harbor

BOSS Look-Down - Improved Sonar

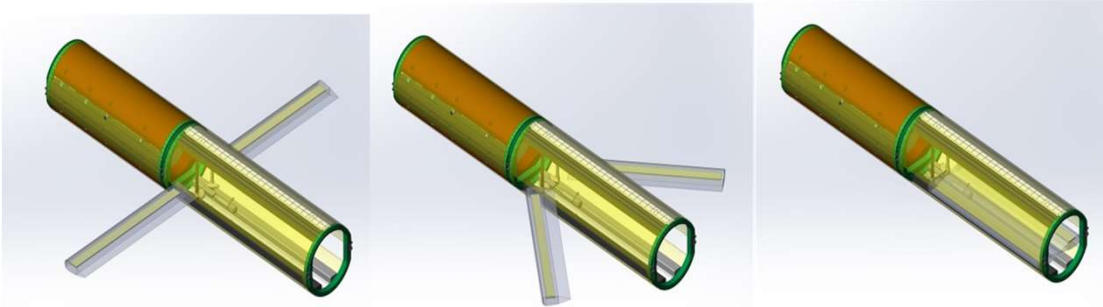


Existing NRL Side-looking SA Sonar



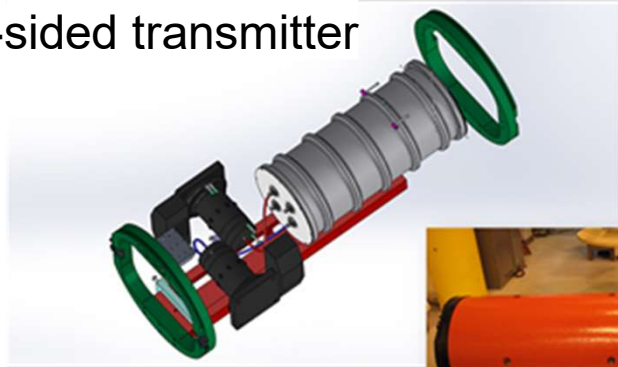
New NRL BOSS Design

64 element retractable receiver wings



- Each wing receiver with 32 hydrophones spaced 0.0375m pushing Nyquist frequency to 20kHz at 2kn.
- Retractable wings to facilitate launch and recovery.

2-sided transmitter

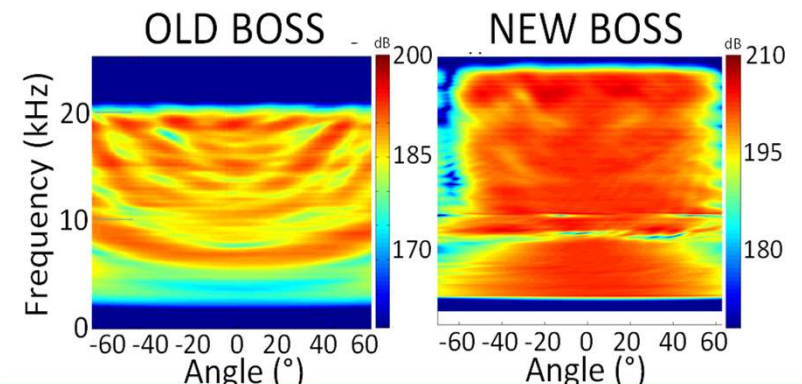


1st at-sea trial
2015



New transmitter section

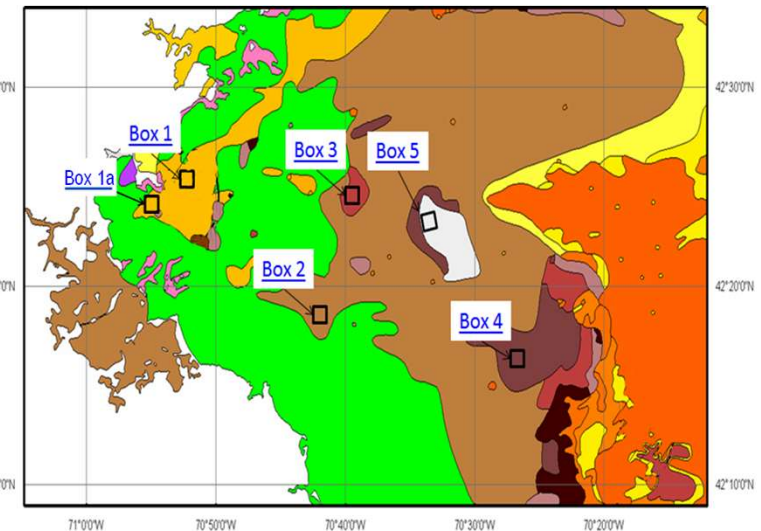
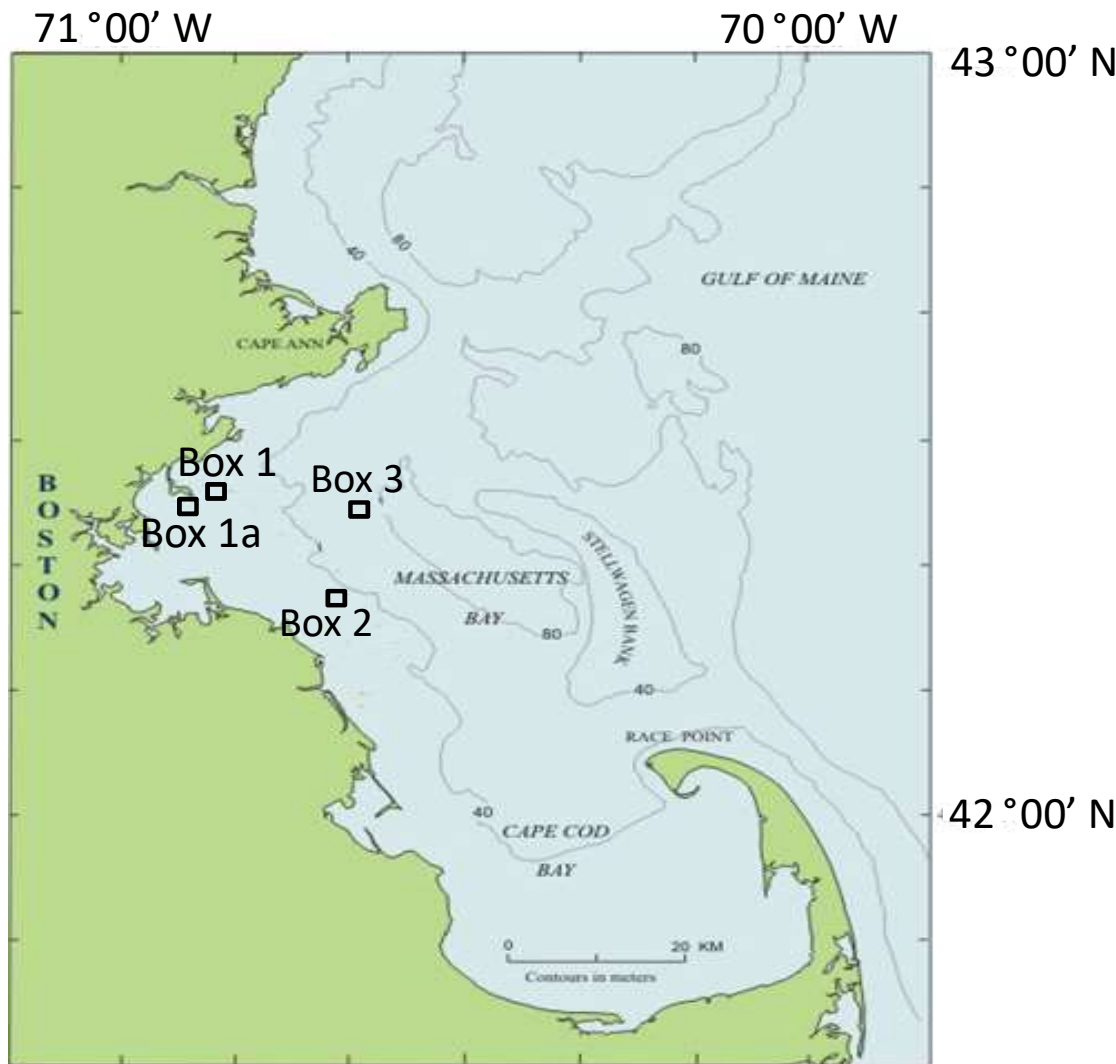
- Stronger: deeper burial.
- More uniform spatial/frequency response.



Demonstration in three ~km² Areas in the Approaches to Boston Harbor

Box 1a,
Box 1, &
Box 2

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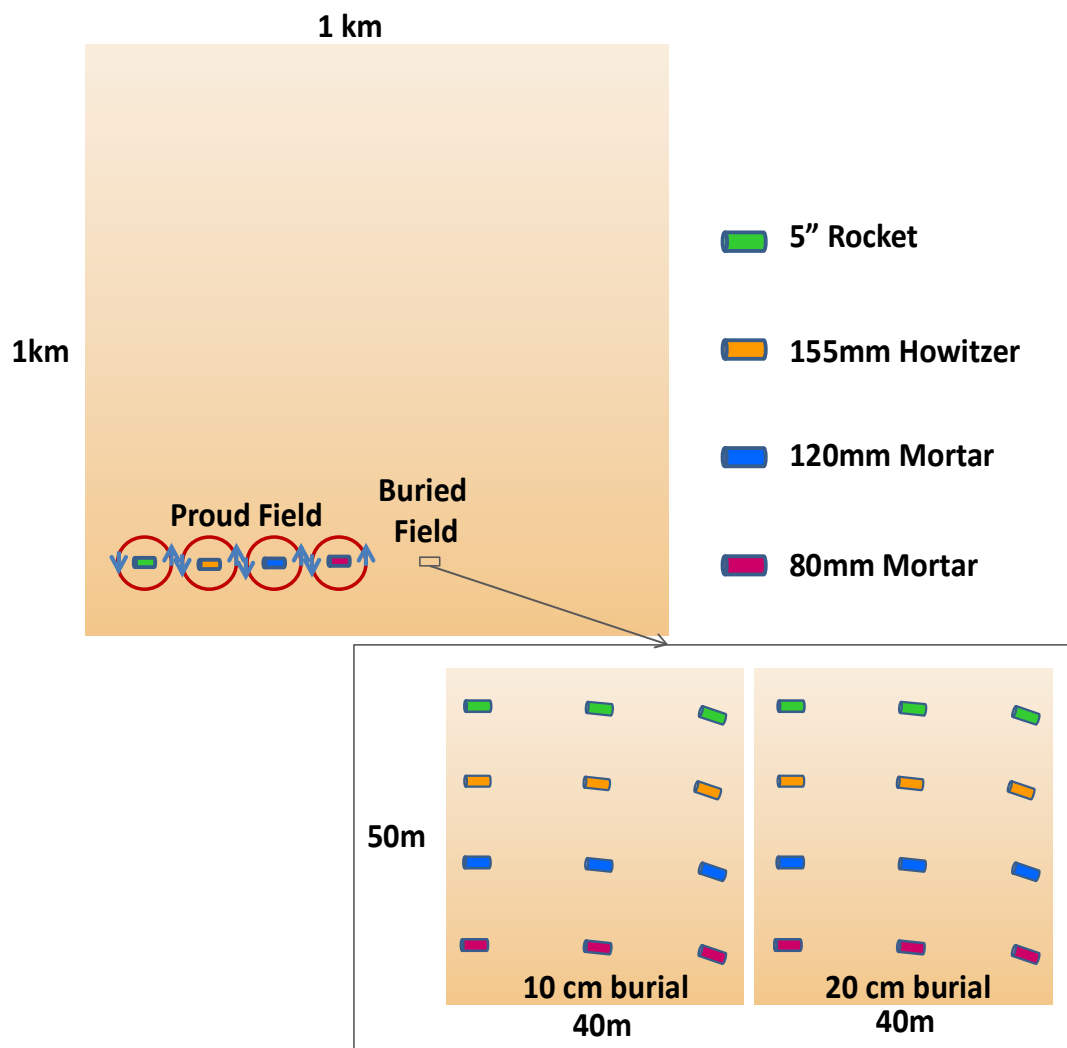


Enhanced Sediments, Boston Area

T Sand	T Fine Sand	T Sand - Shell
T Silty Sand	T Very Fine Sand	T Rock - Sand
T Silt	T Gravelly Silt	T Gravel - Sand
T Silty Clay	T Rock - Sand - Mud	T Gravel - Mud
T Clay	T Rock - Gravel - Sand	T Sand - Mud
T Gravel	T Very Fine Silt	T Muddy Sand
T Silty Gravel	T Fine Silt	T Sandy Mud
T Gravelly Sand	T Medium Silt	T Mud
T Very Coarse Sand	T Coarse Silt	NO DATA
T Coarse Sand	T Granules	LAND
T Medium Sand	T Gravel - Sand - Shell	

RVM Classifier Training Fields

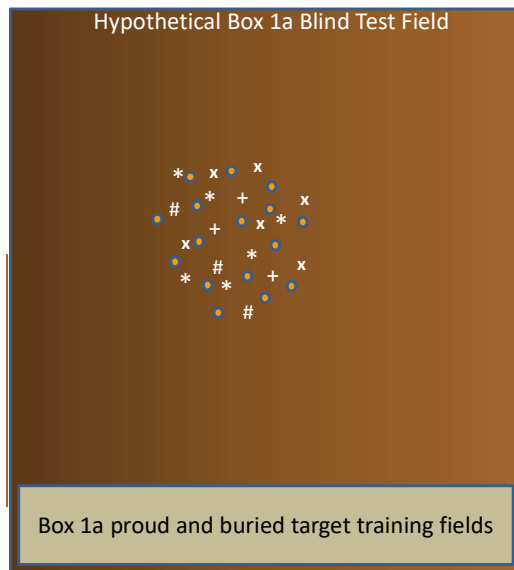
BOX 1a



Test Fields

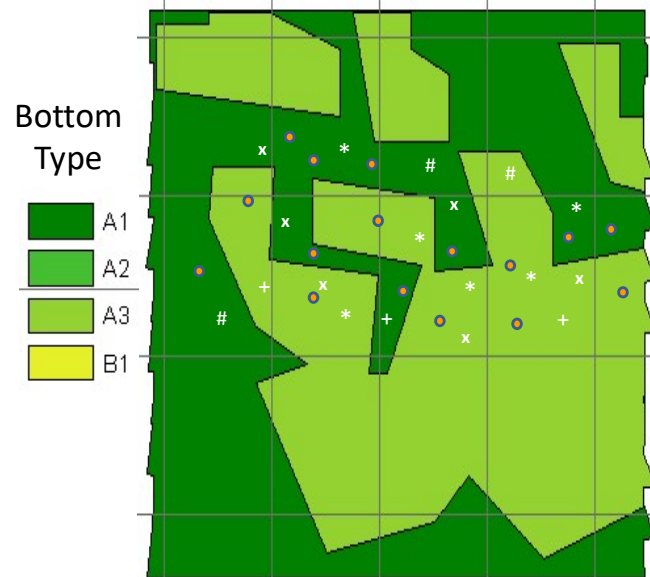
New BOSS Look-Down Test Field

Box 1a

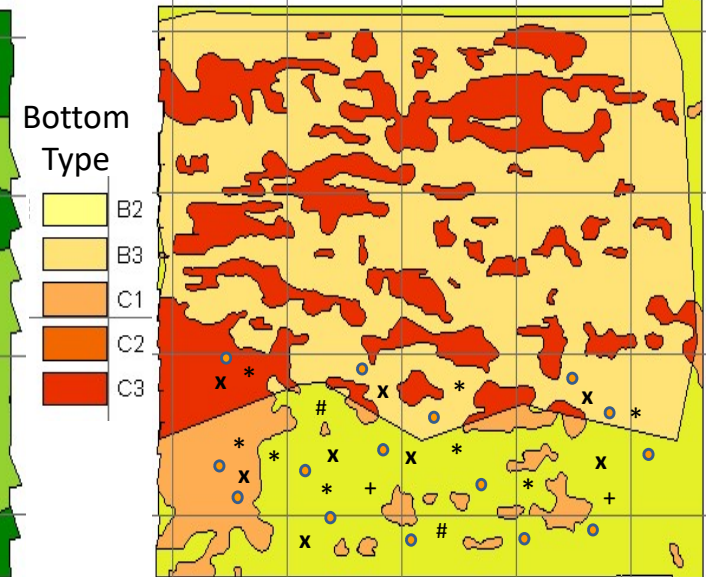


Side-Look Test Fields

Box 1



Box 2



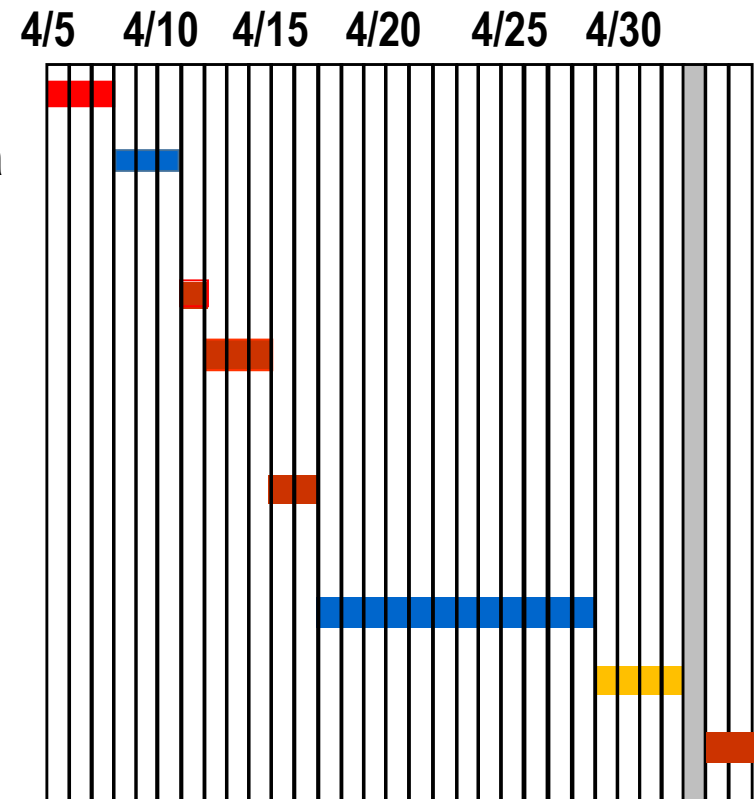
Testing Fields contain 36 buried targets
(18 UXO & 18 Clutter) and 36 proud
targets (18 UXO & 18 Clutter)

NB: Box 2-20 UXO

X 5" Rocket
* 155mm Howitzer
+ 120mm Mortar
80mm Mortar
● Clutter Targets

Shake-down Exercises

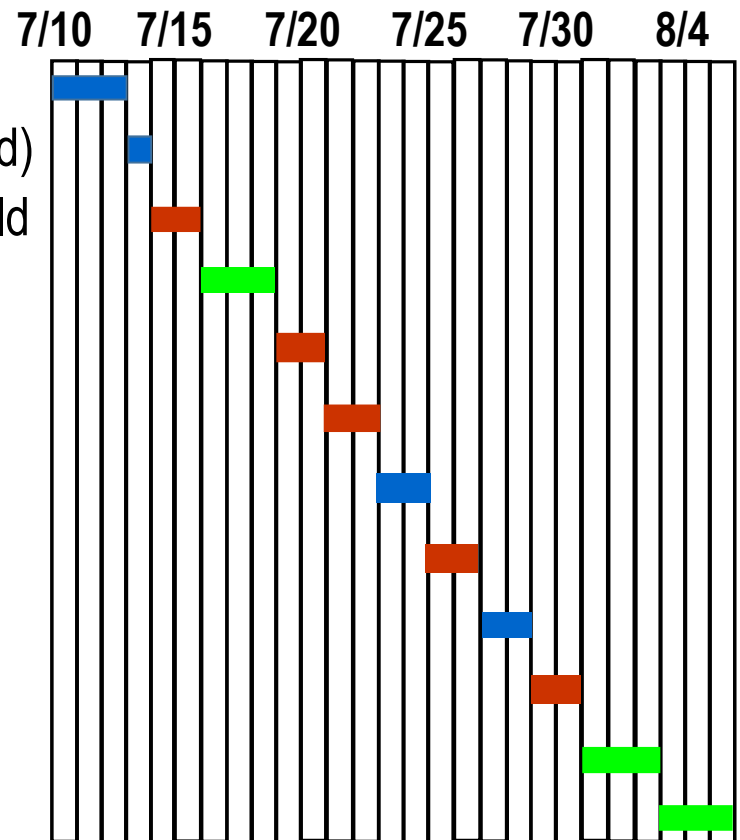
Sub-bottom profiling & high resolution sonar scan in Box 1a
Divers place buried UXO (w/reflectors) & proud UXO in Box 1a training field
High resolution sonar scan over Box 1a training fields
Down-look AUV flown over Box 1a buried target training field (shake down)
Side-look AUV flown over Box 1a proud target training field (shake-down)
Off-line post-processing and assessment
Instrumentation remediation if required
Transport down-look and side-look AUVs back to Box 1a site



Schedule

Demonstration Exercises

Divers bury UXO & clutter in Box 1a test field (w/reflectors)
High resolution sonar map of Box 1a train & test fields (blind)
Down-look AUV flown over Box 1a buried target training field
Down-look AUV flown over Box 1a buried target test field
Side-look AUV flown over Box 1a proud target training field
High resolution sonar maps of Box 1 & Box 2 test areas
Clutter dropped over Box 1 & Box 2 test fields
High resolution sonar maps of Box 1 & Box 2 test fields
UXO dropped over Box 1 & Box 2 test fields
High resolution sonar maps of Box 1 & Box 2 test fields
Side-look AUV flown over Box 1 proud target test field
Side-look AUV flown over Box 2 proud target test field



Performance Objectives: “Look-Down” Sonar

Performance Objective	Metric	Data Required	Success Criteria
Quantitative Performance Objectives			
Detection of all seeded targets	% detected of seeded items	List of all seeded items and their locations	$P_D \geq 0.95$
Classification of UXO	% correctly classified detected seeded UXO	List of all seeded items and their locations	$P_C \geq 0.90$
False alarm reduction: Classification of non-UXO	% correctly classified seeded & native non-UXO that are detected	List of all seeded non-UXO and their location	False alarm rate $P_{FA} < 0.25$
Location accuracy	Error/standard deviation in northing and easting for buried targets	Location of buried items estimated to 0.5m	ΔN and $\Delta E < 0.5m$ σN and $\sigma E < 0.2m$
Target size, shape	Comparison to seeded target dimensions and shape	List of seeded targets, their description and locations	Dimension error: to flight path $\leq \pm 0.12m$ ⊥ to flight path $\leq \pm 0.07m$
Acoustic color	Various target strength (TS) levels	Calibrated UXO echo measurements in controlled environment/matching geometry	TS versus frequency for beam highlight and random aspect integrated TS (RAITS) agree within 3dB.
Orientation & burial depth	Seeded target orientation polar & azimuthal angles; burial depth in meters below sediment surface of highest target point	Burial plan and feedback from diver burial team	Orientation angle error: $\leq \pm 15^\circ$; Depth error: $\leq \pm 0.03m$
Production rate	Number of acres of data collection/day Time required to analyze each target	Log of field work and data analysis time accurate to 15 min	Survey buried targets: >10 acres/hr Analysis time: <5 min/target

Performance Objectives: “Side-Look” Sonar

Performance Objective	Metric	Data Required	Success Criteria
Quantitative Performance Objectives			
Detection of all seeded items	% detected of seeded items	Location of seeded items Complete proud and partially buried UXO target list (from high resolution sonar scans)	$P_D \geq 0.90$ (Box 1) $P_D \geq 0.80$ (Box 2)
Classification of UXO targets	% correctly classified seeded UXO that are detected	Location of seeded items Complete proud and partially buried UXO target list (from high resolution sonar scans)	$P_C \geq 0.90$ (Box 1) $P_C \geq 0.80$ (Box 2)
Acoustic color	Various target strength levels	Calibrated UXO scattering measurements in controlled environment and matching geometry	TS versus frequency for beam highlight and random aspect integrated TS (RAITS) agree within 3dB.
False alarm reduction: Classification of non-UXO	% correctly classified seeded and native non-UXO that are detected	Location of proud and partially buried clutter target list (from high resolution sonar scans)	False alarm rate $P_{FA} \leq 0.25$ (Box 1) $P_{FA} \leq 0.35$ (Box 2)
Location accuracy	Average error standard deviation in northing and easting for buried targets	Location of all targets estimated to 0.5m	ΔN and $\Delta E < 0.5m$ σN and $\sigma E < 0.2m$
Production rate	Number of acres of data collection/day Time required to analyze each target	Log of field work and data analysis time accurate to 15 min	Survey proud and partially-buried targets: >130 acres/hr Analysis time: <5 min/target

Summary



- Structural acoustic (SA) sonar can prosecute buried UXO
- AUV-based SA sonar can provide
 - modest resolution buried target images
 - acoustic color feature classification
- Definitive ESTCP demonstration to take place summer of 2018
- SA sonar compatible with variety of platforms
 - smaller AUVs
 - tow bodies
 - etc.

Major Contributors to the Work Presented here



Angie Sarkissian,	Sotera KeyW
Michael Saniga,	NRL
Harry Simpson,	NRL
Timothy Yoder,	NRL
Zachary Waters,	NRL

Knowledge Check



- The NRL ESTCP 2018 demonstration site includes high clutter density and rough surface sites – **True/False**
- NRL SA sonar technology is also compatible with small AUVs, towed-body vehicles and surface craft – **True/False**
- The P_C and P_{FA} buried target goals for the NRL ESTCP demonstration are **(Multiple Choice)**:
 - (a) $P_C = 1.0$ and $P_{FA} = 0.1$
 - (b) $P_C = 0.9$ and $P_{FA} = 0.25$
 - (c) $P_C = 0.8$ and $P_{FA} = 0.3$
- The improved BOSS sonar for the demonstration includes higher projector levels for deeper targets (**True/False**), higher receiver density for increased bandwidth (**True/False**), higher AUV speeds (**True/False**), and _____.

Contacts and Questions



Points of Contact

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Questions ?